Intrinsic Decay of Quantum Many-Body Systems

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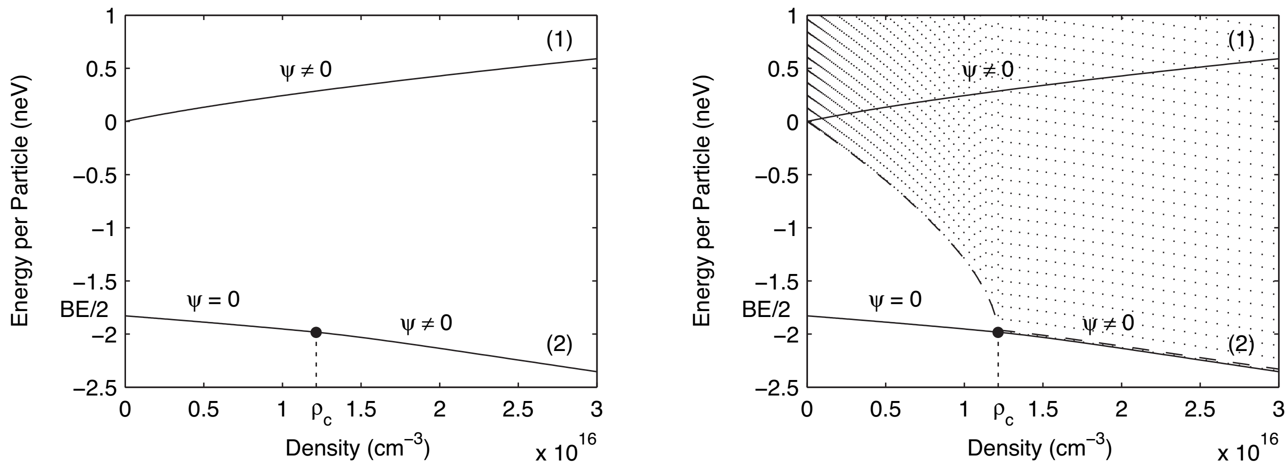
We present a novel many-body decay mechanism inherent in low-density bosonic systems at zero temperature. Exemplified by atomic Bose-Einstein condensates, such systems can be produced experimentally, thereby providing a natural test bed for theoretical models. Specifically, we explore the physics of atom-molecule condensates, coupled through a Feshbach resonance. Using a variational procedure on the corresponding Hamiltonian, an equation of state is found revealing a two-piece collapsing ground state in which only a molecular condensate component is present up to some critical density. Although the usual low-density atomic condensate energy per particle dependence is found in an excited state, it is associated with a complex-valued chemical potential, where the imaginary part quantifies the underlying decay of this state. (A more detailed analysis of this problem is given in Ref. [1].) Using the random phase approximation (RPA), the excited state is seen to decay into collective phonon excitations of the ground state.

Since the production of Bose-Einstein condensates in the laboratory, many schemes have been proposed to control the interatomic interactions in these gases. One such scheme relies on the Feshbach resonance, a phenomenon in which two atoms combine to form an intermediate molecular state. Since the electronic spin configurations of the atoms in this quasi-bound state is different from the initial configurations of the constituent atoms, these two states have an energy difference that can be tuned by an external magnetic field using the Zeeman effect. Consequently, when the binding energy is brought close to the energy of the colliding atoms, the appearance of this molecular state increases thereby modifying the scattering physics of the interaction. Near zero energy, the atomic interactions are described by a single parameter, the s-wave scattering length, a, which is positive for repulsive interactions, but negative for attractive interactions. Thus, by controlling the sign and magnitude of the scattering length, a Feshbach resonance can be used to tune the effective interparticle interactions. Specifically, we treat the case of ^{85}Rb, which has a large, negative background scattering length, a_{bg}= -450a_0 (a_0 = Bohr radius), indicating a collapsing condensate. By exploiting the Feshbach resonance at a magnetic field of approximately 155 G, the scattering length can be tuned to positive values yielding a stable condensate as verified by experiment [2].

A variational analysis of the uniform Hamiltonian reveals much richer physics than expected from simple scattering length arguments. In spite of being in the positive scattering length regime, there is still a collapsing ground state in the system. Moreover, this ground state has a unique two-piece structure, which is best described by the atomic order parameter, ψ, or the mean density of the atomic condensate, ψ^2. Containing no atomic condensate ($\psi = 0$), the first piece of the ground state is composed of only a molecular condensate and correlated atom pairs. Starting at half the molecular binding energy, this section continues down to some critical density ρ_c where it terminates, as shown in Fig. 1(a). At this critical point, the second piece begins where the atomic order parameter, starting from zero, grows with increasing density. Because there is a marked difference in the density dependence of the energy per particle, this solution is of a fundamentally distinct nature from that of ordinary collapsing condensates. In particular, there is a quantum phase transition at the critical density since the compressibility is discontinuous at this point.

In addition to the collapsing ground state, the "stable" solution seen in experiments is associated with a complex-valued chemical potential, $\boldsymbol{\mu}$, that has the density expansion

$$\frac{2m}{\hbar^2}\mu = 8\pi a\rho - i\frac{\sqrt{\pi}}{3}256a^{5/2}\rho^{3/2} + \ldots.$$



(a) (b)

Figure 1—
(a) The real part of the excited state (1) and the collapsing ground state (2) are evaluated at a magnetic field of B = 162.3 G with the parameters given in Ref. [2].
(b) The same figure as in (a) with the shaded region showing the continuum of excitations of the ground state solution. This spectrum not only contains the excited state, but also exhibits an energy gap along the first piece of the ground state.

Relating μ to the energy per particle,

$$e(\rho) = (1/\rho)\int_0^{\rho} \mu(\rho')\,d\rho' \text{, obtains}$$

the observed low-density dependence of $e \sim 4\pi a\rho$. Since the chemical potential plays the role of phase of the atomic field, its imaginary part has a natural interpretation as a decay rate, $\Gamma = \left(256\sqrt{\pi}\hbar/3m\right)a^{5/2}\rho^{3/2}$.

Using the ^{85}Rb parameters of the experiment at $B = 162.3$ G, a decay time of approximately 14 s is obtained, which is in qualitative agreement with the observed time of 10 s [2]. Since particle number is conserved, this decay represents a flux of particles from the excited state into phonon modes of the ground state. Quantitatively, this is confirmed by an RPA analysis where the spectrum of excitations is found by expanding all quantities around the stationary ground state solution. The results of this analysis are shown in Fig. 1(b).

Finally, typical losses in atomic condensates are attributed to two- and three-body mechanisms described using semi-classical arguments. As opposed to these phenomenological loss pictures, we have found that there is an intrinsic decay in these coupled systems, accounted for in the many-body physics of the problem. Most importantly, the predicted dependencies on density and on scattering length can be measured in experimental tests of this theory.

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[1] G.E. Cragg and A.K. Kerman, "A Complex Chemical Potential: Signature of Decay in a Bose-Einstein Condensate," *Phys. Rev. Lett.* (submitted).
[2] S.L. Cornish et al. "Stable ^{85}Rb Bose-Einstein Condensates with Widely Tunable Interactions," *Phys. Rev. Lett.* **85**, 1795 (2000).